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A Note on Vertical Motion Analyses for the Upper Stratosphere

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1. INTRODUCTION

Ever since the stratospheric warming phenomenon was first detected by Scherhag (1952), numerous investigators have discussed the extreme variability that occurs in the circulation patterns throughout the stratosphere and into the mesosphere during these events (for example, Quiroz 1969*a*). While sufficient data have been available for some time in the lower stratosphere to allow hemispheric energy and momentum budget studies to be made for this region during such active periods, the same is not yet true for the upper stratosphere (above approximately 5 mb), where analyses are usually limited to the North American region (Staff, Upper Air Branch 1969). Since the stratospheric warming phenomenon has in many cases been observed to propagate downward, however, there is a need for an examination of the dynamics of the higher levels also. This information including, for example, the high-level vertical motion fields would particularly prove a valuable asset to the present day numerical model studies such as those being pursued by Manabe and Hunt (1968).

Previous studies of upper stratospheric vertical motion fields on a synoptic scale, primarily with the use of meteorological rocketsonde data, have been limited to a few scattered locations for specific short periods. Resultant values range from 1–2 cm sec^{-1} (Kays and Craig 1965) to over 60 cm sec^{-1} (Quiroz 1969*b*), the latter value computed during a pronounced warming of the upper stratosphere. The authors, in each case, employed the thermodynamic energy equation to calculate the vertical motion, with the horizontal advection of temperature being estimated by use of the thermal wind equation and observed wind changes with height. While this technique is limited in time and in the vertical direction only by the length of record at the station, it is limited in the horizontal direction by substantial regions without any rocketsonde data.

We have employed the weekly constant-pressure analyses for the 5-, 2-, and 0.4-mb surfaces constructed from rocketsonde observations (Staff, Upper Air Branch 1969) to calculate all terms in the adiabatic vertical motion equation at selected grid points within the analysis region. The advection term then was computed directly from the geostrophic wind and analyzed temperature fields. This technique has the advantage of greater spatial coverage than the previous method, but its resolution in time and height is limited in that the analyses are available only on a weekly basis and at certain pressure levels.

Our ultimate objective is to investigate the upper stratospheric vertical motion fields and the associated dynamic aspects during several recent midwinter stratospheric warmings: January 1967, December 1967–January 1968, and December 1969–January 1970. In view, however, of the current interest in numerical model studies of the midwinter warming events and the relative disparity of the recent vertical motion calculations, we felt that there would be sufficient interest in some of our preliminary results to warrant publication at this time.

For this pilot study, the analyses are restricted to the 2-mb level for the period Jan. 11 and 18, 1967; this particular time being chosen because it was a period of pronounced warming, but restricted to the upper stratosphere. Preliminary computations of the vertical motion field at 5, 2, and 0.4 mb during the major warming of December 1967, however, indicate that the magnitudes of the above vertical velocities are representative of this type of event.

2. PROCEDURE

The computations of vertical motions have been made from the adiabatic version of the first law of thermodynamics in the form:

$$W=-\frac{1}{(\Gamma-\gamma)}\left(\frac{\partial T}{\partial t}+\mathbf{V}_P\cdot\nabla_P T\right) \tag{1}$$

where W is the vertical motion (positive upward), γ the environmental lapse rate, Γ the adiabatic lapse rate; and the terms in parentheses are, respectively, the local temperature change and the horizontal advection. The adiabatic heating term was neglected in this study since a heating rate at these heights of $\sim -3°$C day^{-1} (Murgatroyd and Goody 1958) would have contributed less than 0.5 cm sec^{-1} to the calculated vertical motions.

After careful consideration of the scales of motion portrayed in the constant-pressure analyses, a grid was devised whereby vertical motions could be calculated at every 20° of longitude from 35° W. to 175° W. at latitudes of 25° N., 45° N., and 65° N. After these initial computations were made, additional points were calculated if warranted by any individual analyses.

The finite-difference approximations used for the derivatives on the right-hand side of equation (1) were as follows:

a) The $\partial T/\partial t$ was approximated at each grid point by subtracting the temperature value the week previous from the value at map time, that is $\partial T/\partial t=\{T(\text{map time})-T(\text{week previous})\}\times\{1\text{ week}\}^{-1}$.

b) The $\mathbf{V}_P\cdot\nabla_P T$ was evaluated using the geostrophic approximation to calculate winds. In all computations, centered differences were used, with 5° latitude or longitude as the difference interval, that is $\partial T/\partial x=\{T(x+\Delta\lambda)-T(x-\Delta\lambda)\}\ \{2\ a\cos\phi\ \Delta\lambda\}^{-1}$ where a is the radius of the earth, ϕ the latitude, and $\Delta\lambda$ is equal to 5° in radians.

c) The $\partial T/\partial z$ was estimated by reconstructing at each grid point a temperature profile from the pertinent 5-, 2-, and 0.4-mb temperature analyses and then subtracting the temperature value at 1 km below 2 mb from that at

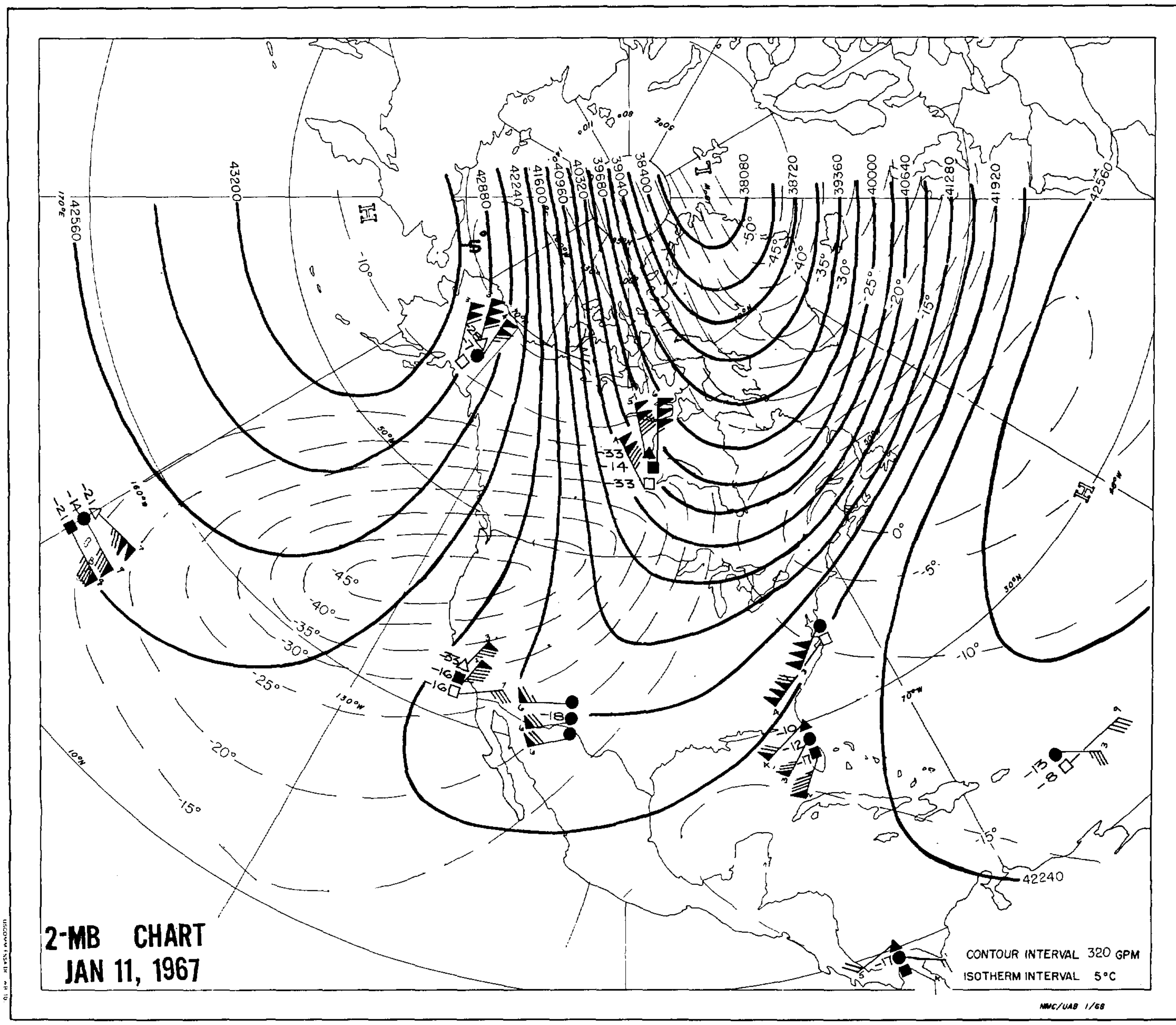

FIGURE 1.—The 2-mb chart for Jan. 11, 1967. Plotted rocketsonde winds are in knots and temperatures in degrees Celsius. Full barb is shown for each 10 kt and a flag for each 50 kt. The open triangle denotes data 2 days previous to the map date, the solid triangle 1 day previous, the dot the map date, the solid square 1 day subsequent, and the open square 2 days following the map date. Contour interval is at 320 gpm and isotherm interval at 5°C.

1 km above 2 mb, that is

$$\frac{\partial T}{\partial z}=\{T(z_{2mb}+1)-T(z_{2mb}-1)\}\{2\text{ km}\}^{-1}.$$

At these heights, this term is generally positive and several factors smaller than the adiabatic lapse rate.

While it is very difficult to assess quantitatively the inaccuracies inherent in this technique, a general description of various considerations is given by Craig and Lateef (1962). Considering the various aspects (especially the accuracy of the analyses), we believe that our computations of W should be reliable in both sign and magnitude, except possibly in the neighborhood of zero vertical motion. One point that should be emphasized, though, is that as Kays and Craig (1965) illustrate, the degree of vertical smoothing employed in the rocketsonde wind data can be very important when calculating vertical motions at single stations. In the present technique, we believe that the additional constraint applied—that the temperature analyses be consistent with both the observed temperatures and the thermal wind calculations (Staff, Upper Air Branch 1969)—alleviates this difficulty and results in more accurate determinations.

3. RESULTS

The 2-mb analyses for Jan. 11 and 18, 1967, are shown in figures 1 and 2, respectively. Initially, there were two

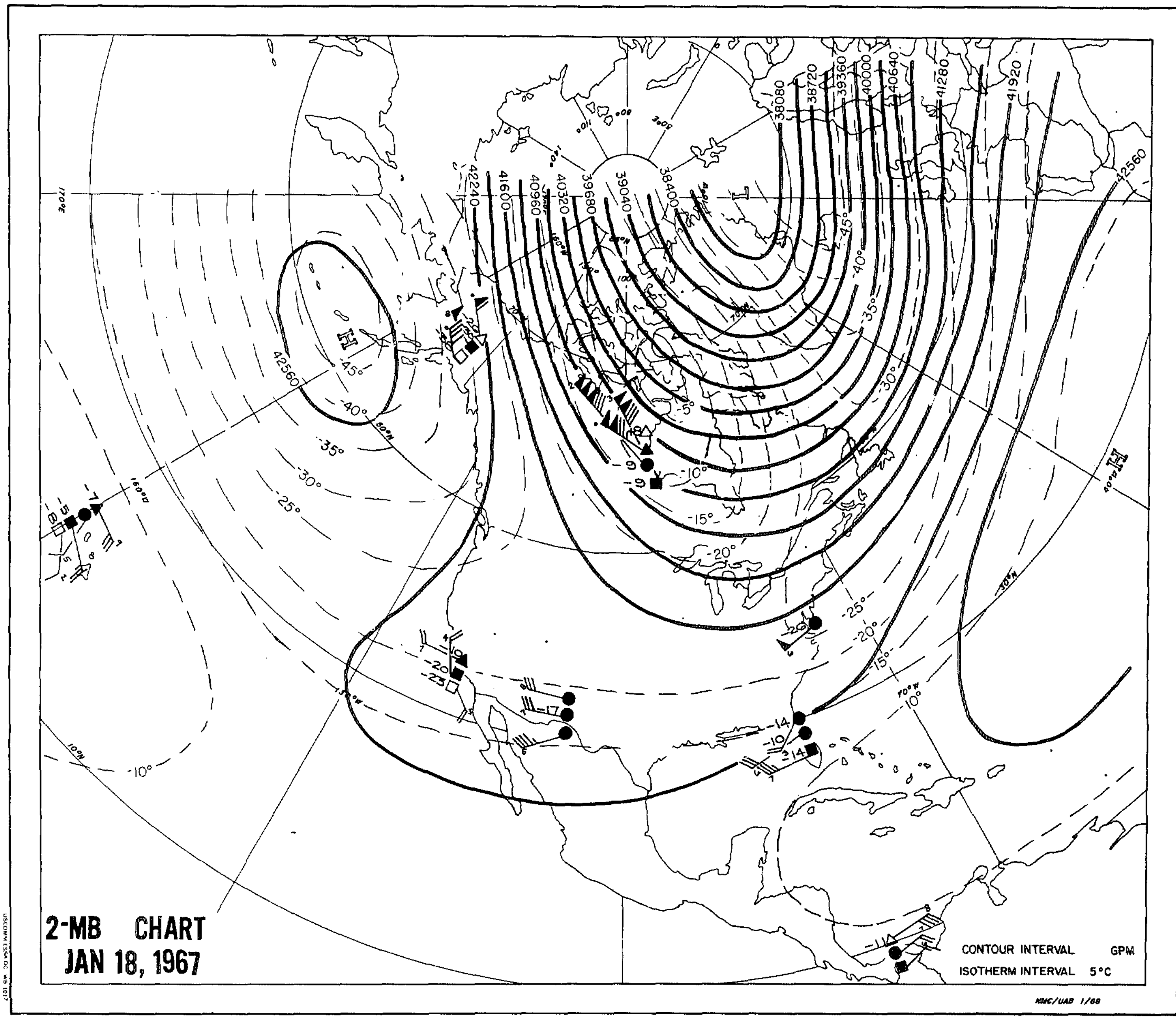

FIGURE 2.—The 2-mb chart for January 18, explanation as in figure 1.

warm centers in the thermal field, one located near Alaska and the other over the northeastern United States. Greatest inland penetration of the warm air occurred on about the 18th of January. Thereafter, the warm air decreased in intensity and eventually disappeared. Since the circulation pattern did not change in a drastic manner (no wind reversals occurred), this event may be classified as a "minor" midwinter warming. A similar sequence of events was observed at the 5- and 0.4-mb levels, but no such pronounced changes in either the temperature or height fields were observed as low as 10 mb.

Figures 3 and 4 depict the vertical motion analyses for January 11 and 18, respectively. In agreement with the results of Kays and Craig (1965) and Quiroz (1969*b*), the sign and magnitude of the vertical motion were essentially determined by the horizontal advection term. Thus, it is not surprising that the regions of upward motion tend to be in the region of warm air advection, and vice versa. The magnitudes of the vertical motions are of the order of 3–9 cm sec^{-1}, which is of the same order found by Craig and Lateef (1962) at the 25-mb level during the 1957 warming. While the magnitude of our calculated vertical velocities is far less than that found by Quiroz (1969*b*), it should be realized that the synoptic situation during his analysis period was extremely different from ours. Observed winds during his analysis period reached a value of 385 kt at 39 km, while maximum winds observed during our series were only about 160 kt. In addition, his temperature increases were nearly twice as great as ours.

Unfortunately, analyses used in this study are not hemispheric, so that it is not possible to break down the kinetic and potential energies into their zonal and eddy components. One can, however, estimate the internal transformation of total potential to total kinetic energy

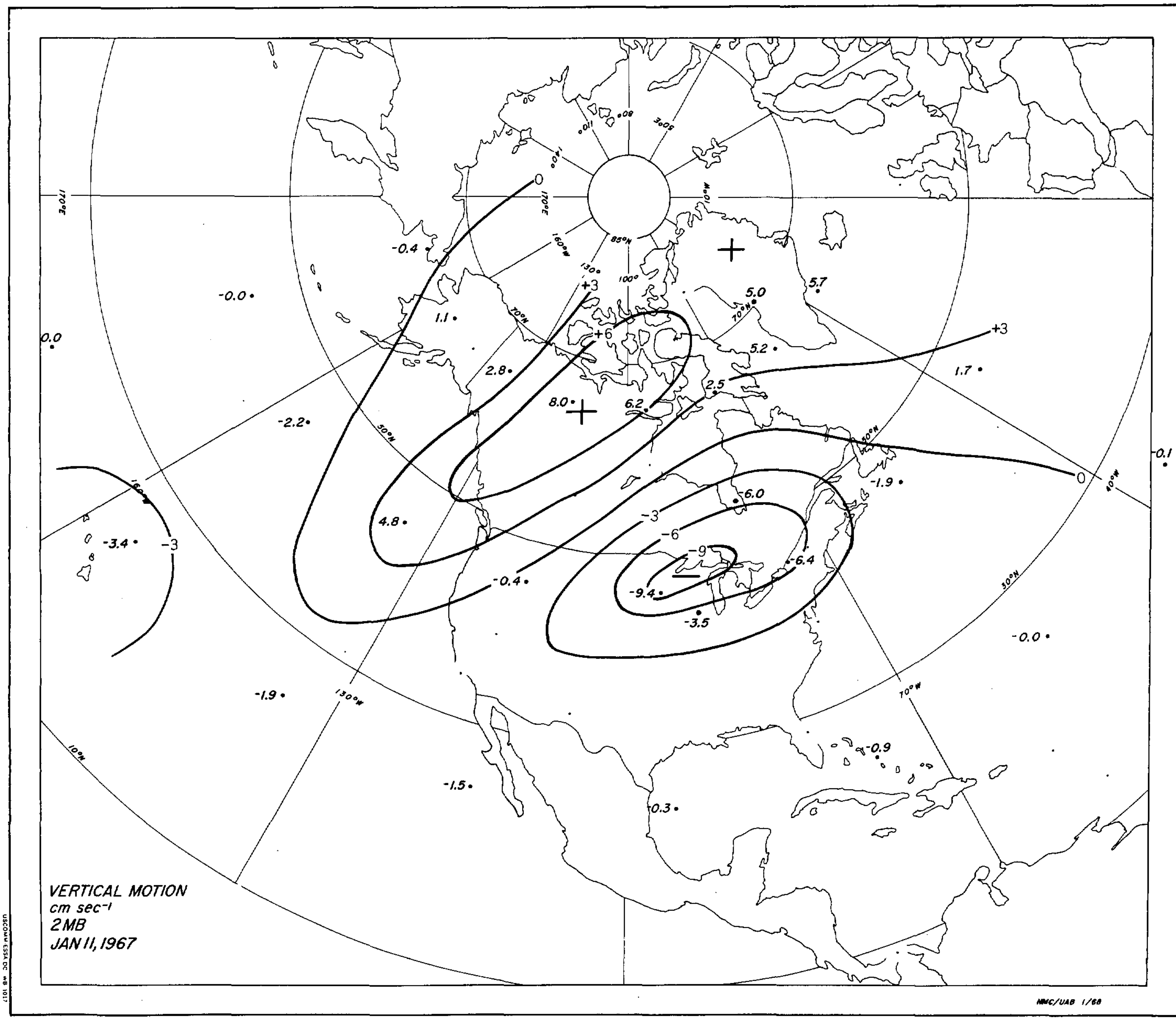

FIGURE 3.—The 2-mb vertical motion analysis for Jan. 11, 1967; units, cm sec^{-1}.

by evaluating the integral $-\int\int\int \omega\alpha(dp/g)dxdy$ over the mass of an infinitesimal layer (for example, Miller 1967), where ω is the instantaneous pressure change dp/dt and α is the specific volume.

The values obtained for this transformation (evaluated between 35° W.–175° W. and 25° N.–65° N.) were -0.826 ergs cm^{-2} sec^{-1} mb^{-1} and $+0.461$ ergs cm^{-2} sec^{-1} mb^{-1} for the 11th and 18th, respectively. While due caution is needed in interpreting these results in view of the limited analysis region and the neglect of the diabatic term, the suggestion is that the internal transformation is from kinetic energy to potential energy during the warming, with a reversal of this transformation leading to the declination of the warming.

Interestingly, Manabe and Hunt (1968) calculated a similar order of magnitude for the eddy conversion of potential to kinetic energy at their top three levels during their simulated warming event.

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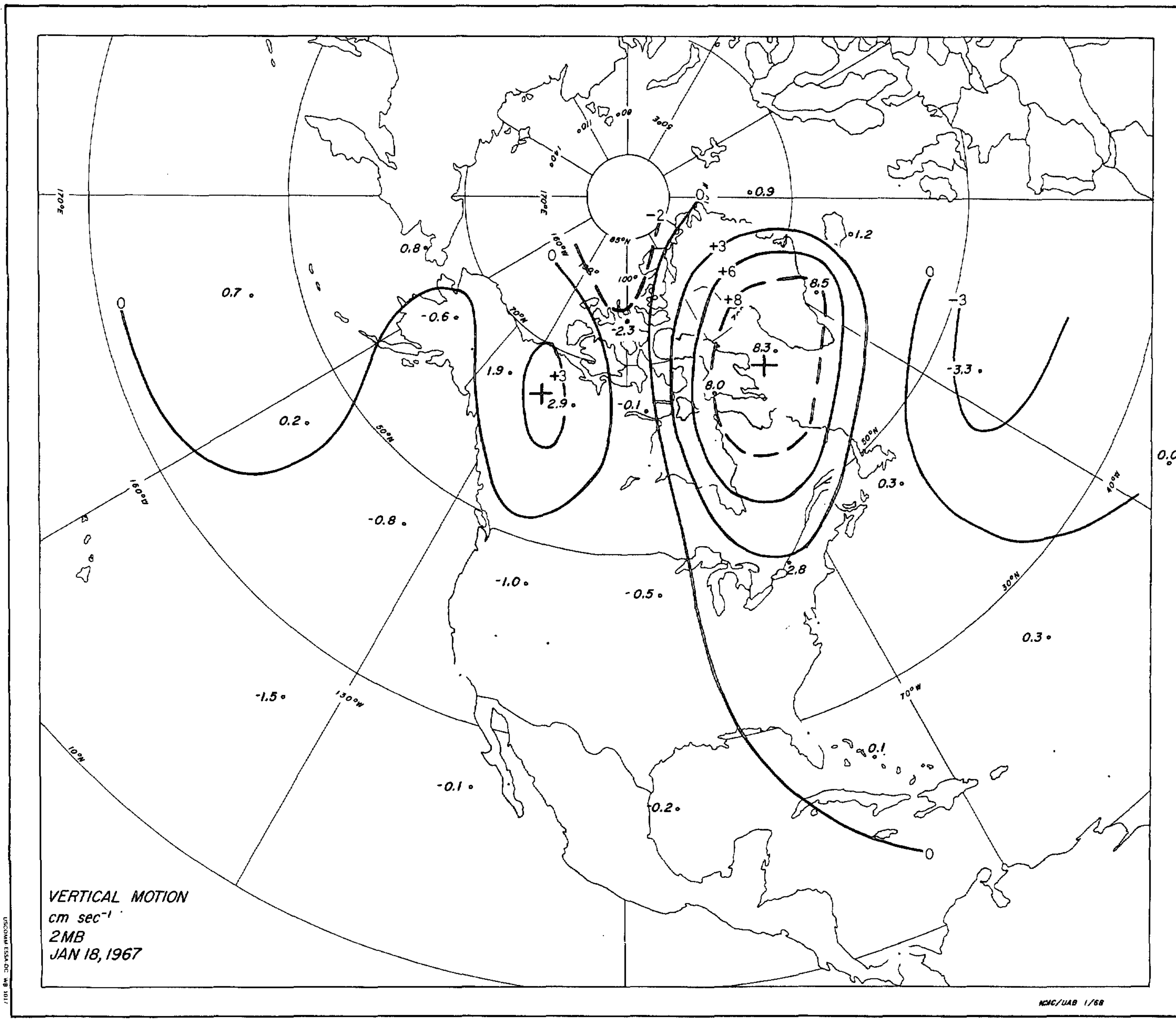

FIGURE 4.—The 2-mb vertical motion analysis for Jan. 18, 1967; units, cm sec^{-1}.

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